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(54) **AUTOMATED FABRICATION SYSTEM IMPLEMENTING 3-D VOID MODELING**

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See application file for complete search history.

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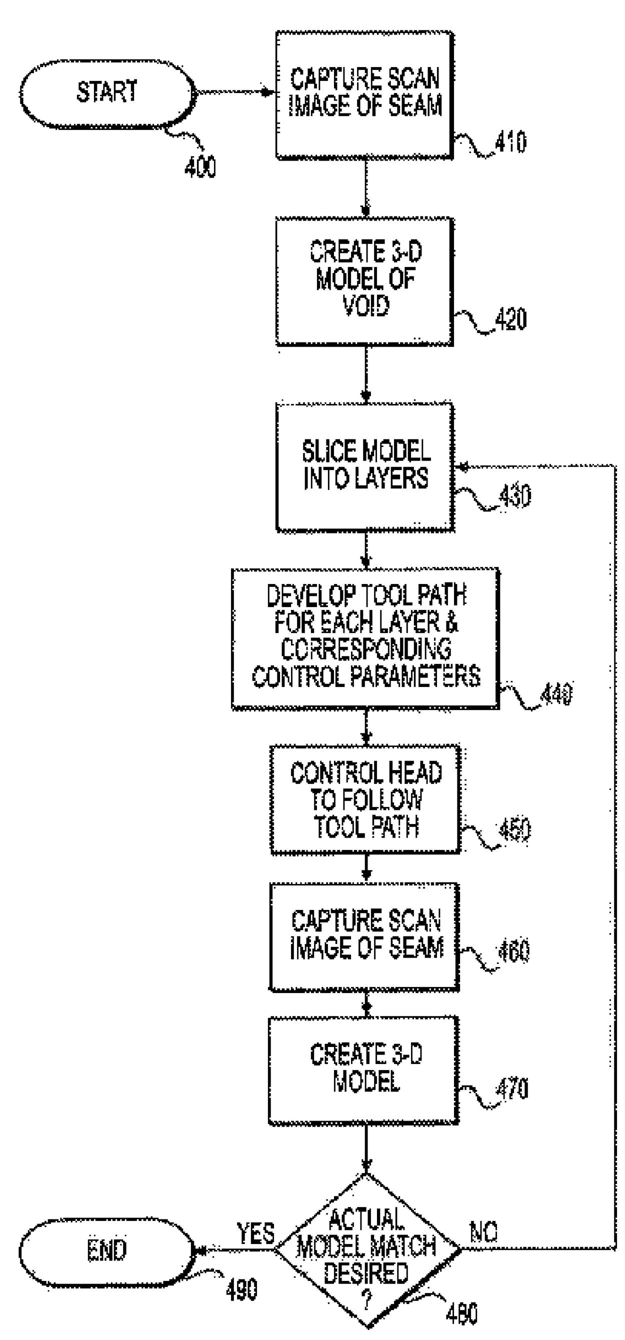
(57) **ABSTRACT**

A fabrication system is disclosed for use in joining two components of a work piece. The fabrication system may have a mount configured to hold the work piece with a void to be filled with material. The fabrication system may also have a scanner configured to capture at least one image of the void, a robotic fabrication device movable relative to the mount, and a controller in communication with the scanner and the robotic fabrication device. The controller may be configured to generate a model of the void based on the at least one image, and to slice the model into at least one layer. The controller may also be configured to develop a tool path for each of the at least one layer, and to cause the robotic fabrication device to deposit material within the void based on the tool path.

19 Claims, 3 Drawing Sheets



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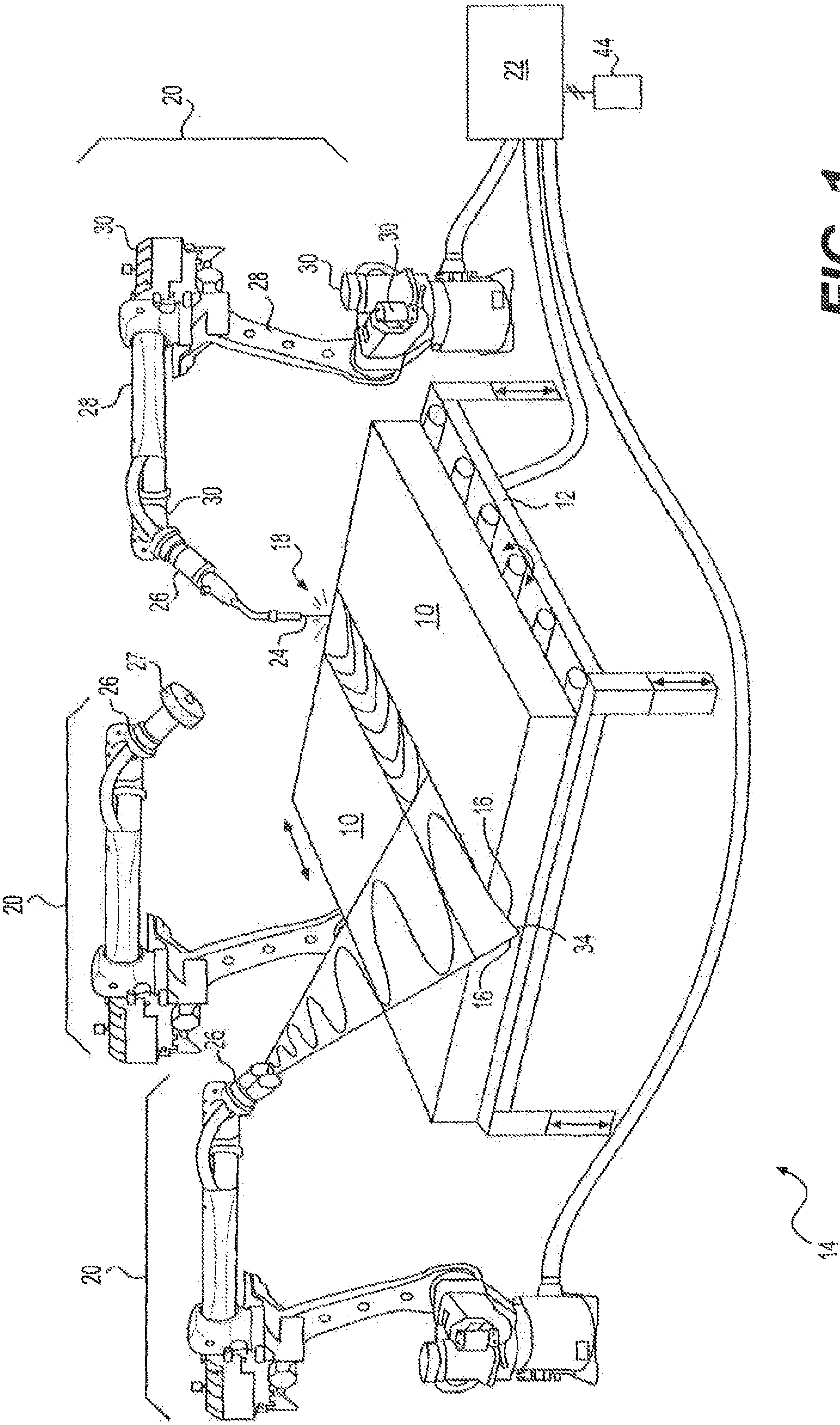


FIG. 1

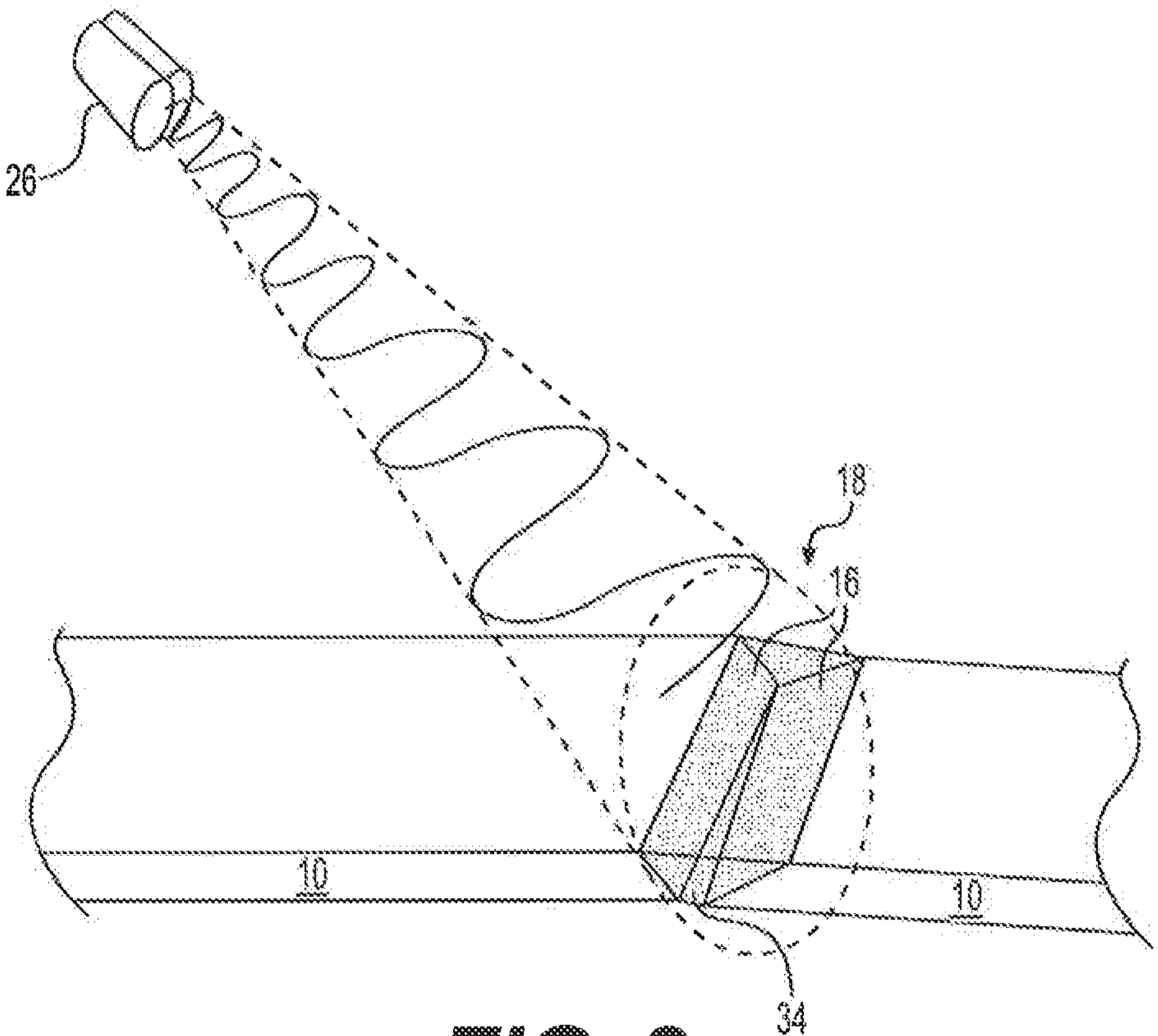


FIG. 2

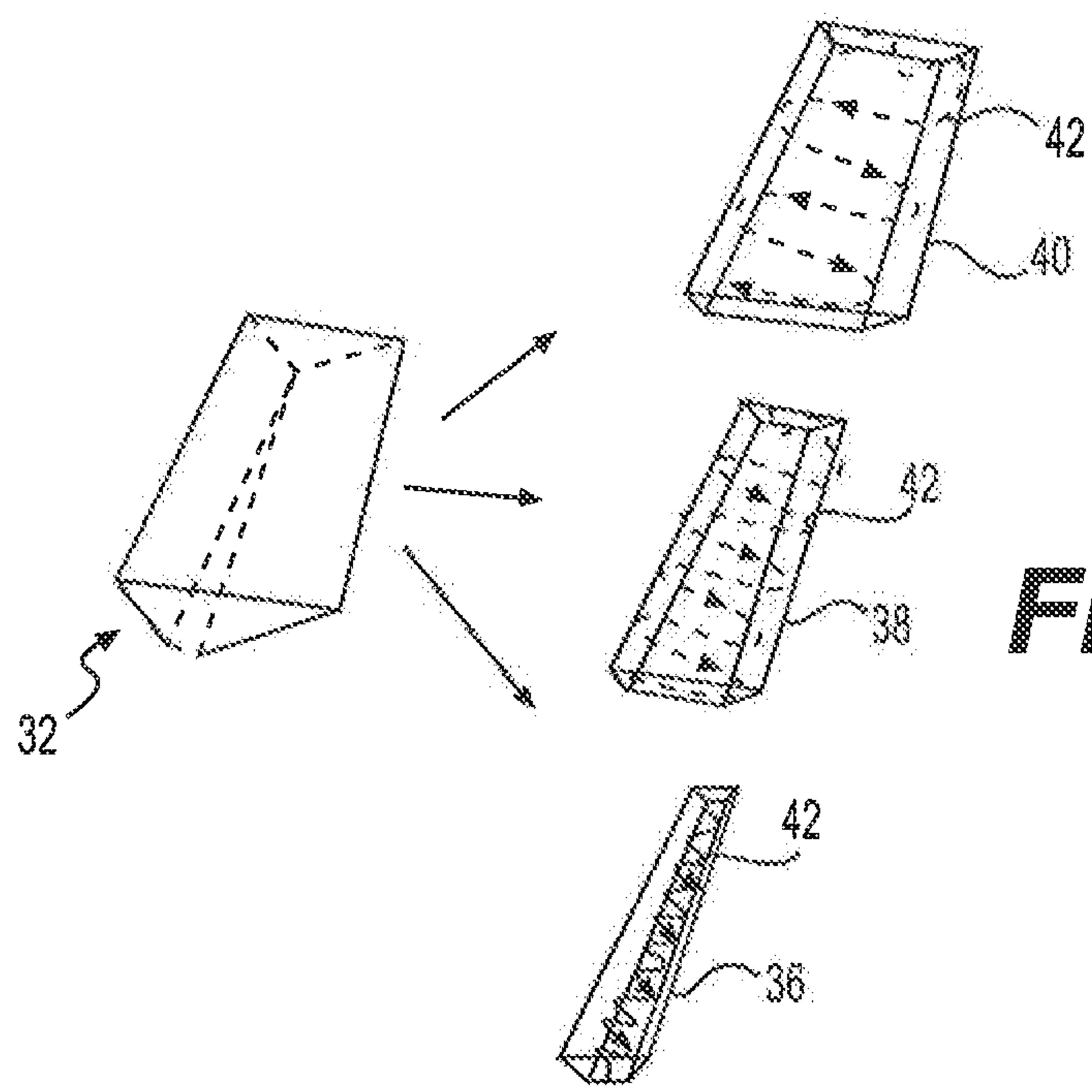
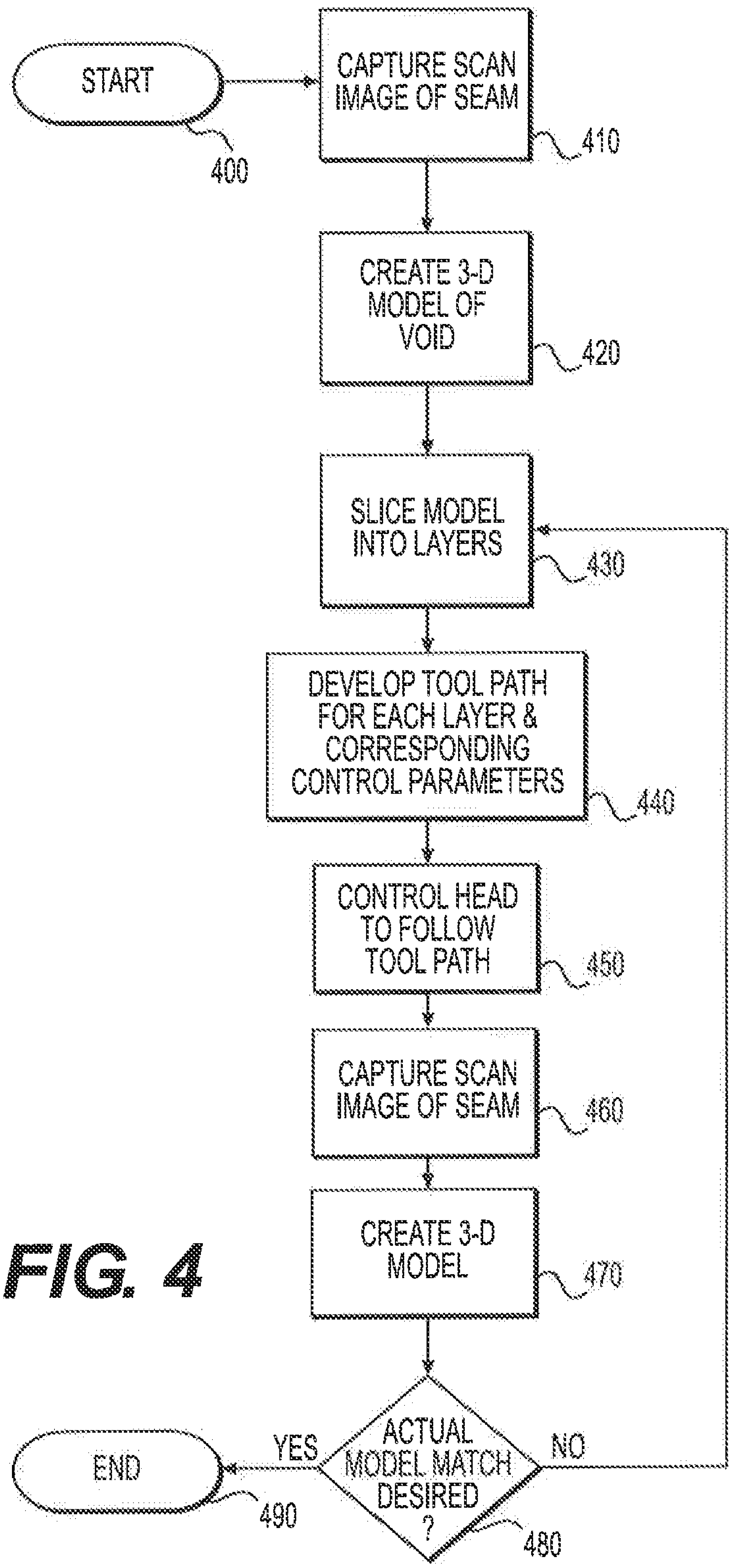


FIG. 3



START
400
CAPTURE SCAN IMAGE OF SEAM
410
CREATE 3-D MODEL OF VOID
420
SLICE MODEL INTO LAYERS
430
DEVELOP TOOL PATH FOR EACH LAYER & CORRESPONDING CONTROL PARAMETERS
440
CONTROL HEAD TO FOLLOW TOOL PATH
450
CAPTURE SCAN IMAGE OF SEAM
460
CREATE 3-D MODEL
470
ACTUAL MODEL MATCH DESIRED ?
480
YES
NO
END
490

FIG. 4

AUTOMATED FABRICATION SYSTEM IMPLEMENTING 3-D VOID MODELING

TECHNICAL FIELD

The present disclosure relates to a fabrication system and, more particularly, to an automated fabrication system that implements 3-D void modeling.

BACKGROUND

Welding is a fabrication process used to join together two components of similar material through the application of heat and a filler material. Welding can be done manually or autonomously via a welding robot. Manual welding can be inconsistent in both quality and appearance. This can be especially true when the seam is welded by different technicians.

When welding a seam using a robot welder, the robot is generally pre-programmed to execute the same sequence of movements at the same locations and with the same welding parameters (e.g., speed, power, feed rate, etc.) each time the robot is presented with the two components. In this way, a very repeatable weld may be created. However, even though the same type of components can be repeatedly welded by the same robot, each component may be slightly different due to manufacturing tolerances, and/or presented to the robot in a slightly different manner (e.g., position and/or orientation). As a result, the void between the components that is to be filled with molten material may not always be the same shape and size. Yet the robot welder may still execute the same weld sequence. Accordingly, each weld may turn out different and, in some situations, the resulting weld may not have the quality and/or appearance required for a particular application.

An exemplary welding method is disclosed in U.S. Patent Application Publication 2013/0197683 of Zhang et al. that published on Aug. 1, 2013 ("the '683 publication"). In particular, the '683 publication discloses a method for manufacturing a part in layers. The method includes slicing a 3-D model of the part into layers, the number of layers depending on a required dimensional accuracy of the part. The method also includes planning a modeling path according to slicing data of the 3-D model, and generating numerical control codes for model processing. The method further includes performing fused deposition modeling of wire material onto a substrate layer using a welding gun according to a track specified by the numerical control code for each layer.

Although the method of the '683 publication may allow for creation of an irregular 3-D object through welding, the '683 publication does not disclose origination of the corresponding model. In addition, while the method may be capable of producing a part, it may lack the necessary control to join two components together. Further, the '683 publication may only be capable of material deposition, which may limit broad applicability.

The present disclosure is directed to overcoming one or more of the shortcomings set forth above and/or other problems of the prior art.

SUMMARY

In one aspect, the present disclosure is directed to an automated fabrication system. The automated fabrication system may include a mount configured to hold a work piece with a void to be filled with material. The fabrication system

may also include a scanner configured to capture at least one image of the void, a robotic fabrication device movable relative to the mount, and a controller in communication with the scanner and the robotic fabrication device. The controller may be configured to generate a model of the void based on the at least one image, and to slice the model into at least one layer. The controller may also be configured to develop a tool path for each of the at least one layer, and to cause the robotic fabrication device to deposit material within the void based on the tool path.

In a second aspect, the present disclosure is directed to another automated fabrication system. This system may include a mount configured to hold a work piece, and a scanner configured to capture at least one image of the work piece. The system may also include a robotic fabrication device movable relative to the mount, and a controller in communication with the scanner and the robotic fabrication device. The controller may be configured to generate a model of the work piece based on the at least one image, and to slice the model into at least one layer. The controller may further be configured to develop a tool path for each of the at least one layer, and to cause the robotic fabrication device to perform a fabrication process based on the tool path.

In a third aspect, the present disclosure is directed to a method of fabricating a work piece. The method may include capturing at least one image of a void in the work piece, and generating a model of the void based on the at least one image. The method may also include slicing the model into at least one layer, developing a tool path for each of the at least one layer, and automatically depositing material into the void based on the tool path.

BRIEF DESCRIPTION OF THE DRAWING

FIG. **1** is a diagrammatic illustration of an exemplary disclosed fabrication system;

FIG. **2** is an isometric illustration of components being joined by the fabrication system of FIG. **1**;

FIG. **3** is a diagrammatic illustrations of exemplary steps performed by the fabrication system of FIG. **1**; and

FIG. **4** is a flowchart depicting the steps illustrated in FIG. **3**.

DETAILED DESCRIPTION

FIG. **1** illustrates two components **10** that are held within a mount **12** during processing by a fabrication system **14**. In the disclosed embodiment, both components **10** are generally planer and held flat against mount **12**, with beveled edges **16** of components **10** brought near each other at a seam **18**. Components **10** may be joined to each other to form an integral work piece. It is contemplated that components **10** used to fabricate the work piece may have any shape and be oriented in any manner (e.g., perpendicular to each other), as desired. It is further contemplated that one or more of edges **16** may have a shape other than beveled, such as a blunt shape, a dual beveled edge, etc., and/or that the adjacent edges **16** of seam **18** may be integral to the same component **10**.

As used herein, the term "work piece" is intended to cover an objected having undergone or intended to undergo a fabrication process. In the disclosed embodiments, multiple components **10** are joined together during the fabrication process to form the work piece. However, in other embodiments, the work piece may begin as a single component and have fabrication processes performed thereon to add or remove material from the work piece.

Mount **12** may be configured to hold components **10** generally stationary relative to each other, and either hold components **10** stationary or move components **10** relative to fabrication system **14** during a fabrication (e.g., material deposition and/or removal) process. For example, mount **12** may be equipped with one or more actuators (not shown) that are configured to linearly move components **10** in a length wise direction of seam **18**, move components **10** in a transverse direction, raise/lower components **10**, and/or tilt components **10** toward and/or away from fabrication system **14**.

Fabrication system **14** may include mechanisms that cooperate to autonomously fill seam **18** with material and join edges **16** to each other, or to remove material from components **10** (e.g., to prepare seam **18** for filling and/or to finish seam **18** after filling). For example, fabrication system **14** may include, among other things, one or more robotic fabrication devices (RFD) **20**, and a controller **22** configured to regulate movements of each RFD **20**.

RFD **20** may have any number of processing heads **26**, one or more arms **28** operatively connected to each head **26**, and a plurality of actuators **30** configured to move arms **28** and/or heads **26** during a fabrication process in response to commands from controller **22**. In a first example, the fabrication process is a deposition process such as welding, and head **26** is configured to feed or otherwise advance a metal rod or wire **24** toward seam **18** while simultaneously directing current through rod **24**. In a second example, the fabrication process is a removal process such as grinding or cutting, and head **26** is configured to power a removal tool (e.g., to rotate a grinding wheel **27** or to energize a plasma arc cutter). In a third example, the fabrication process is a scanning process such as image capturing, and head **26** includes a scanning device such as a camera **29** or an RF scanner. It is contemplated that a single head **26** could be configured to perform all three processes, that RFD **20** may have three different heads **26** that are independently operable (shown in FIG. **2**), and/or that RFD **20** may have three heads **26** that are separately attachable one-at-a-time to a single set of arms **28**. Other configurations may also be possible.

Controller **22** may control operations of fabrication system **14** in response to the image captured by the scanning head **26** and/or one or more sets of instructions contained within memory. Specifically, in response to image signals received from the scanning device of RFD **20**, controller **22** may generate a 3-D model **32** (shown in FIG. **3**) of a void **34** (shown in FIG. **2**) formed at seam **18** by the space between beveled edges **16**. Controller **22** may then slice the 3-D model **32** into layers (e.g., in a first layer **36**, a second layer **38**, and a third layer **40**), and generate tool paths **42** that should be followed by the deposition and/or removal heads **26** of RFD **20**. Controller **22** may then selectively adjust power sent to and/or operation of heads based on the tool paths **42**. It is contemplated that controller **22** may also communicate with actuators **30** of mount **12** and be configured to selectively move components **10** relative to heads **26** based on input from RFD **20** and/or the instructions stored in memory, if desired.

Controller **22** may embody a single microprocessor or multiple microprocessors that include a means for controlling an operation of fabrication system **14**. Numerous commercially available microprocessors may perform the functions of controller **22**. Controller **22** may include or be associated with a memory for storing data such as, for example, an operating condition, design limits, performance characteristics or specifications of fabrication system **14** and components **10**, and/or operational instructions. Various other known circuits may be associated with controller **22**, including power supply circuitry, signal-conditioning circuitry, solenoid driver circuitry, communication circuitry, and other appropriate circuitry. Moreover, controller **22** may be capable of communicating with other components of fabrication system **14** via either wired or wireless transmission and, as such, controller **22** may be disposed in a location remote from fabrication system **14**, if desired.

In some embodiments, controller **22** may rely on feedback during a fabrication process (deposition and/or removal process) to affect the process. For example, controller **22** may rely on sensory feedback, such as temperature feedback from a sensor **44** (e.g., an infra-red thermal sensor—referring to FIG. **1**), to help ensure that the process is proceeding as expected. In some deposition applications, it may be possible for a temperature induced within components **10** to exceed a threshold level at which characteristics (e.g., brittleness, hardness, warping, etc.) of the resulting work piece deviate from desired characteristics. In these applications, controller **22** may be configured to adjust a feed rate, a travel rate, a power level, a depth, a cooling delay, etc., based on the feedback.

Controller **22** may be configured to cause heads **26** to fill seam **18** with weld material and/or to remove material at seam **18** (e.g., in preparation for filling and/or after filling to finish seam **18**) according to one or more algorithms stored in memory. Different steps of these algorithms are visually depicted in FIGS. **2** and **3**, and shown in the flowchart of FIG. **4**. These figures will be discussed in more detail in the following section to further illustrate the disclosed concepts.

INDUSTRIAL APPLICABILITY

The disclosed fabrication system may be used to join components in a manner that produces a quality work piece, even when the components are irregular and/or arranged in an unintended manner. In particular, the disclosed fabrication system may be configured to take into account the irregularity of the components and/or the unintended arrangement of the components through modeling, create tool paths based on the modeling, and automatically deposit or remove material by following the tool paths. The result may be improved weld saturation, improved joint strength, and improved appearance. Operation of fabrication system **14** will now be described in detail with respect to FIGS. **2-4**.

Operation of fabrication system **14** can generally be divided into three different phases, including a preparation phase, a fabrication phase, and a finishing phase. At start of the preparation phase (Step **400**—referring to FIG. **4**), controller **22** may gather information regarding components **10** to be welded. This information may include one or more scanned images of the space between edges **16**. As shown in FIG. **2**, the scanning head **26** may capture the images of seam **18** that are used to create the model **32** of void **34** (Step **410**). As components **10** may each be slightly different (even when components **10** have the same part numbers) and arranged in a slightly different manner (even when robotically positioned or positioned using jigs), the space between edges **16** will always have a slightly different size, shape, and volume. And if the same fabrication sequence was used to fill the different spaces, the resulting joints could be different and, in some instances, have undesired characteristics. The images captured by the scanning head **26** may include and help account for these differences.

As shown in FIG. **3**, controller **22** may use the images captured by the scanning head **26** to create a unique 3-D model **32** associated with each pairing of components **10**

(Step **420**). The 3-D model **32** may represent void **34** located at seam **18** that should be filled with material to complete the joining of components **10**. Model **32** may be created using methods known in the art.

As also shown in FIG. **3**, controller **22** may then be configured to slice model **32** into multiple layers **36-40** (Step **430**). In the disclosed embodiment, each of these layers may have a thickness about equal to a thickness of material that can be deposited by head **26** in a single pass. In other words, the deposition head **26** may be configured to deposit material in a bead formation (i.e., an elongated formation having a circular or elliptical cross-section), and the thickness of layers **36-40** may be about the same as a diameter of the bead formation. In another embodiment, the thickness of layers **36-40** may be a multiple of the bead diameter, and require multiple passes for a sufficient amount of the material to be deposited.

Controller **22** may then be configured to determine one or more tool paths **42** for each layer **36-40** that head **26** should follow during the fabrication phase, and corresponding control parameters (Step **440**). In some embodiments, tool path **42** may include a preliminary segment that should be followed by a material removal head **26** in preparation for subsequent material deposition segments. In particular, it may be possible that portions of components **10** (e.g., portions of edges **16**) need to be removed (e.g., flattened, polished, recessed, straightened, etc.) and/or shaped (e.g., corners rounded and/or dams built) in order to properly receive fill material. In other embodiments, the tool paths **42** may be associated with only material deposition. In either embodiment, tool paths **42** should allow for the total volume of each layer **36-40** of model **32** to be completely filled before fabrication of the adjacent layer begins. Each tool path **42** may be generated based on a size, shape, and/or volume of void **34** and the corresponding layer **36-40**, and deposition characteristics of head **26**. The deposition characteristics may include, among other things, a deposition feed rate, a deposition cross-sectional area, and a thermal loading imparted to the work piece by the deposition. In addition, each controller **22** may determine control parameters for head **26** corresponding to each segment of the tool path **42** based on characteristics of the deposition head **26**, the material being deposited, and/or the material of components **10**. For example, a thickness and a trajectory of travel path **42** (e.g., length, direction, location, and/or turn radius) may vary for different components and/or different deposition heads **26**. In addition, a wire feed rate, a head travel speed, a current, and other control parameters may also vary based on component and/or head characteristics. Controller **22** may then follow one or more different algorithms stored in memory to fill seam **18** with weld material and complete the fabrication phase (Step **450**).

In some embodiments, feedback from sensor **44** may affect completion of the fabrication phase. In particular, as head **26** is removing material from and/or depositing material into seam **18**, sensor **44** may provide feedback regarding the process. In one example, the feedback includes a signal indicative of a temperature of either of components **10** and/or of the deposited material. This signal may then be used by controller **22** to adjust the operation (e.g., to adjust the feed rate, travel rate, thickness, cooling delays, and/or current).

After the fabrication phase is complete, controller **22** may cause the scanning head **26** to generate additional images of seam **18** during the finishing phase (Step **460**), which may provide an indication as to a quality of seam **18**. Controller **22** may again be configured to use the images provided by the scanning head **26** to generate a new 3-D model of void **34** within seam **18** (Step **470**), and to compare the new model to a desired model of void **34** and/or to the initial model **32** that was generated before void **34** was filled (Step **480**). And based on this comparison, controller **22** may determine if void **34** has been adequately filled with deposited material and not overfilled. If void **34** is determined to be adequately filled, the process may end (Step **490**:Yes).

However, if at step **480**, controller **22** determines that some space is left unfilled within void **34** (e.g., an amount greater than a threshold amount and/or an amount at a critical area of seam **18**—Step **480**:No), control may return to step **430**. That is, controller **22** may cause additional material to be deposited at seam **18** or, if too much material was deposited at seam **18** (i.e., such that the material overflowed seam **18**), controller **22** may cause material to be removed.

In some embodiments, controller **22** may also use the second 3-D model for calibration purposes. In particular, if the second model does not substantially match the desired model of void **34**, controller **22** may conclude that the factors used to slice layers **36-40** and/or to determine travel paths **42** require adjustment. Controller **22** may iteratively and/or periodically make adjustments to these factors until the second model substantially matches the desired model.

It is contemplated that the disclosed fabrication system may be configured to perform a process similar to that disclosed in FIG. **4**, but that involves only or primarily material removal, if desired. For example, controller **22** may be configured to use images captured by the scanning head **26** of a protrusion (as opposed to a void) on component **10**. Controller **22** may then generate the 3-D model **32** of the protrusion based on the images, and slice model **32** into layers **36-40**. Controller **22** may then generate tool paths **42** for each layer that can be used by the removal head **26** to grind or cut away the protrusion from component **10**.

The disclosed fabrication system may produce high quality work pieces in a time efficient manner. Specifically, because the disclosed system may generate 3-D models that are unique to each pairing and arrangement of components **10**, the ensuing fabrication process that is controlled based on the unique model may be of high quality. And the ability to assess the process at its completion and to selectively improve the process based on the assessment may help to improve the process at each iteration. Further, the disclosed process may be applicable to both material deposition and material removal.

It will be apparent to those skilled in the art that various modifications and variations can be made to the disclosed fabrication system. Other embodiments will be apparent to those skilled in the art from consideration of the specification and practice of the disclosed fabrication system. It is intended that the specification and examples be considered as exemplary only, with a true scope being indicated by the following claims and their equivalents.

What is claimed is:

1. A fabrication system, comprising:

a mount configured to hold a work piece having a void to be filled with material;

a scanner configured to capture at least one image of the void;

a robotic fabrication device movable relative to the mount; and

a controller in communication with the scanner and the robotic fabrication device and configured to:

generate a 3-D model of the void based on the at least one image during a preparation phase prior to a deposition of material within the void during a fabrication phase;

slice the 3-D model into a plurality of layers during the preparation phase;

develop a tool path to be followed by the robotic fabrication device during the fabrication phase for each of the plurality of layers, wherein the tool path to be followed by the robotic fabrication device for each of the plurality of layers is developed during the preparation phase prior to the fabrication phase; and

cause the robotic fabrication device to deposit material within the void during the fabrication phase based on the tool path developed during the preparation phase prior to the deposition of material within the void.

2. The fabrication system of claim **1**, wherein:

the robotic fabrication device is a welder configured to deposit the material in a bead formation; and

each of the plurality of layers has a thickness about equal to a diameter of the bead formation.

3. The fabrication system of claim **1**, wherein the controller is configured to develop the tool path based at least in part on a shape of the void, a volume of the void, and one or more characteristics associated with the robotic fabrication device.

4. The fabrication system of claim **3**, wherein the characteristics associated with the robotic fabrication device include a deposition feed rate, a deposition cross-sectional area, and a thermal loading.

5. The fabrication system of claim **1**, wherein:

the at least one image includes at least a first image; and

the controller is further configured to cause the scanner to capture at least a second image after deposition of material by the robotic fabrication device, the at least a second image providing an indication of a quality of the deposition.

6. The fabrication system of claim **5**, wherein:

the 3-D model is a first 3-D model;

the tool path is a first tool path for each of the plurality of layers; and

the controller is further configured to:

generate a second 3-D model based on the at least a second image;

make a comparison of the second 3-D model to a desired model; and

selectively develop a second tool path based on the comparison.

7. The fabrication system of claim **6**, wherein the robotic fabrication device is further configured to remove material.

8. The fabrication system of claim **7**, wherein the controller is further configured to selectively cause the robotic fabrication device to remove material from the work piece prior to deposition of material based on the first 3-D model.

9. The fabrication system of claim **8**, wherein the controller is further configured to selectively cause the robotic fabrication device to remove or deposit material based on the second 3-D model during completion of the second tool path.

10. The fabrication system of claim **6**, wherein the controller is configured to selectively implement a calibration procedure based on the comparison.

11. The fabrication system of claim **1**, further including a thermal sensor configured to generate a signal indicative of a temperature of the work piece during deposition of material by the robotic fabrication device, wherein the controller is in further communication with the thermal sensor and configured to selectively adjust the tool path based on the signal.

12. A fabrication system, comprising:

a mount configured to hold a work piece;

a scanner configured to capture at least one image of the work piece;

a robotic fabrication device movable relative to the mount; and

a controller in communication with the scanner and the robotic fabrication device and configured to:

generate a model of the work piece based on the at least one image during a preparation phase prior to the performance of a fabrication process;

slice the model into at least one layer during the preparation phase prior to the performance of a fabrication process;

develop a tool path for each of the at least one layer during the preparation phase prior to the performance of a fabrication process; and

cause the robotic fabrication device to perform the fabrication process during a fabrication phase based on the tool path developed during the preparation phase prior to the performance of a fabrication process.

13. The fabrication system of claim **12**, wherein the fabrication process includes a deposition process and a removal process, and the robotic fabrication device includes one or more processing heads, the one or more processing heads including a processing head configured to advance a metal rod toward the work piece while directing current through the rod during the deposition process and a processing head configured to power a grinding wheel during the removal process.

14. A method of fabricating a work piece, comprising:

capturing at least one image of a void in the work piece during a preparation phase, wherein the preparation phase is prior to a deposition of material into the void;

generating a model of the void based on the at least one image during the preparation phase;

slicing the model into at least one layer during the preparation phase;

developing a tool path for each of the at least one layer during the preparation phase; and

automatically depositing material into the void during a fabrication phase based on the tool path generated during the preparation phase prior to the deposition of material into the void.

15. The method of claim **14**, wherein the model is a 3-D model.

16. The method of claim **14**, wherein:

the at least one layer includes a plurality of layers;

automatically depositing the material includes automatically depositing the material in a bead formation; and

each of the plurality of layers has a thickness about equal to a diameter of the bead formation.

17. The method of claim **14**, wherein developing the tool path includes developing the tool path based at least in part on a shape of the void, a volume of the void, and deposition characteristics.

18. The method of claim **14**, wherein:

the at least one image includes at least a first image;

the model includes a first model;

the tool path includes a first tool path; and

the method further includes:

capturing at least a second image after deposition of material;

generating a second model based on the at least a second image;

making a comparison of the second model to a desired model; and

selectively developing a second tool path based on the comparison.

19. The method of claim **18**, wherein the method further includes automatically removing material based on at least one of the first and second models.

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